

# Neon Abundances from a *Spitzer*/IRS Survey of Wolf-Rayet Stars

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## ABSTRACT

We report on neon abundances derived from *Spitzer* high resolution spectral data of eight Wolf-Rayet (WR) stars using the forbidden line of [Ne III] 15.56 microns. Our targets include four WN stars of subtypes 4–7, and four WC stars of subtypes 4–7. We derive ion fraction abundances  $\gamma$  of  $\text{Ne}^{2+}$  for the winds of each star. The ion fraction abundance is a product of the ionization fraction  $Q_i$  in stage  $i$  and the abundance by number  $\mathcal{A}_E$  of element  $E$  relative to all nuclei. Values generally consistent with solar are obtained for the WN stars, and values in excess of solar are obtained for the WC stars.

*Subject headings:* stars: abundances — stars: mass-loss — stars: winds — stars: Wolf-Rayet

## 1. Introduction

Wolf-Rayet (WR) stars continue to attract the attention of many researchers because they are evolved massive stars that are useful for testing stellar evolutionary models and because they have extremely massive winds (Lamers *et al.* 1991; Meynet & Maeder 2003). We report on infrared observations of [Ne III] 15.56 microns for eight WR stars, each of a different spectral subtype (see Tab. 1), obtained with the *Spitzer* Infrared Spectrograph (IRS) using the Short-High (SH) mode in the 10–20 micron band. Details about the *Spitzer* telescope and particularly the IRS instrument can be found in Houck *et al.* (2004). Our program targeted four nitrogen-rich WN stars, and four carbon-rich WC stars. Subtypes WN4–WN7 and WC4–WC7 were selected to avoid complications associated with the late subtypes, namely that the WC8 and WC9 types often show dust production (e.g., van der Hucht *et al.* 1981; Williams 1997; Monnier *et al.* 2007) and the WN8 types are asso-

ciated with significant variability (Antokhin *et al.* 1995).

Forbidden lines are useful in studies of massive stellar winds for several reasons. Foremost, they can be used to derive ion fraction abundances  $\gamma_{i,E}$  (for ionization stage  $i$  of element  $E$ ) from the total flux of line emission that can be used to test models of massive star evolution (Barlow, Roche, & Aitken 1988). The lines form at very large radii in the wind, typically where the wind density is around  $10^5 - 10^6 \text{ cm}^{-3}$  associated with the critical densities of common IR forbidden lines, and so their line profile shapes also relate directly to the geometry of the wind flow. For example in a spherically symmetric wind, one expects a canonical “flat-topped” rectangular line profile (Castor 1970), whereas for an axisymmetric wind, the profile morphology will be double-horned or centrally peaked (Ignace & Brimeyer 2006). Moreover, at such large radii, the properties of the winds can be taken as asymptotic, and so ratios involving  $\gamma_{i,E}$  for different ions within a species represent the

large-scale ionization balance in the wind (e.g., Ignace *et al.* 2001), information that can be used to constrain the ionizing radiation field of the star.

Stellar evolution of massive stars predicts that neon should not be enriched owing to nuclear processing until reaching the stage of WC stars, at which point neon enrichment by factors of 10 and more are to be expected (Maeder 1983; Meynet & Maeder 2003). We show that our *Spitzer* observations generally conform to the expectation of neon enrichment. In section 2, we briefly discuss the spectra obtained with the IRS/SH instrument. In Section 3, data for [Ne III] 15.56 is presented for each target, and neon abundances are derived. Conclusions based on this study are given in Section 4.

## 2. Observations and Data Reduction

Target selection was based on several criteria. Sources were to be relatively bright in the infrared and should be single stars. We selected targets to span a range of WN and WC subtypes. All of the observations were made with *Spitzer*/IRS between February and April of 2005. The raw data were reduced using version 13.2 of the pipeline. Additional reduction involved visual inspections of each BCD frame for quality. The IRSCLEAN package was used to remove bad or hot pixels and other instrumental defects. The main reduction was conducted with the IRS tool SMART (Higdon *et al.* 2004). Calibration files supplied by the SMART team were used in the calibration process.

The data were crosschecked with the actual DCE FITS images to ensure that any missed bad pixels were eliminated, and that any stray instrumental effects were noted and corrected. The spectral resolving power of the IRS/SH is about 600 (Houck *et al.* 2004). All data were smoothed using a Gaussian with  $\sigma = 0.025\mu\text{m}$ . The method of obtaining ion fraction abundances  $\gamma_{i,E}$  depends only on the total flux in the emission line, and so line profile data displayed in this paper already include subtraction of the continuum flux level at the line. As an example, Figure 1 shows part of the IRS/SH spectrum for one of our brighter sources, WR 90. The solid histogram is the smoothed IRS/SH data. The dashed line shows for our fit to the continuum level. Continuum fits for all of our sources were obtained through polynomial least-squares fitting to selected line-free regions in the SH band. The continuum-subtracted data in the immediate vicinity of [Ne III] are displayed in Figure 2. These have not been corrected for reddening, which is

quite minor at these wavelengths for our sources.

## 3. Neon Abundances

The line spectra are rich in He II recombination lines. The forbidden line of [Ne III] 15.56 is present and generally prominent in the spectra. Barlow *et al.* (1988) were the first to determine values of  $\gamma_{i,E}$  from forbidden lines of WR stars, in that case for  $\gamma$  Vel. The principle is that forbidden lines are optically thin and form predominantly in the large radius, constant velocity flow. Being thin, the observed total flux of forbidden line emission relates to a volume integral of the line emissivity. This integral converges and can be used to relate the ion fraction abundance  $\gamma_{i,E}$  to the total line flux. Deriving ion fraction abundances does require knowledge about the wind mass-loss rate, terminal speed, and the distance to the source. Formally  $\gamma_{i,E}$  sets a lower limit for the abundance of an atomic species, since the total abundance  $\gamma_E = \sum_i \gamma_{i,E}$ . However, it is common that an element will be found in a predominant stage of ionization, with other ion stages represented in mainly trace amounts (e.g., Drew 1989). An advantage of the [Ne III] line is that one expects  $\text{Ne}^{2+}$  to be an abundant or dominant ion for many WR stars for the subtypes studied in our sample. The ionization potential (IP) for  $\text{He}^{1+}$  is 54 eV. This is to be compared to the IP of 40 eV for  $\text{Ne}^{1+}$ , and 63 eV for  $\text{Ne}^{2+}$ . At large radii helium is singly ionized (Schmutz & Hamann 1986; Hillier 1987), or even doubly ionized in many cases (Hamann, private comm). So  $\text{Ne}^{2+}$  can be especially useful for tracing nuclear processing, since one reasonably expects it to represent the total abundance of neon in many instances.

The method of Barlow *et al.* (1988) has already been applied to a number of WR stars, for example in studies by Willis *et al.* (1997), Morris *et al.* (2000), Dessart *et al.* (2000), and Ignace *et al.* (2001) using *Infrared Space Observatory* (ISO) observations. A ground-based study by Smith & Houck (2005) determined values of  $\gamma$  for  $\text{Ne}^{1+}$  for three late WN stars and a pair of late WC stars. Ion fraction abundances for EZ CMa (or WR 6, a WN4 star) based on *Spitzer* spectra have been given by Morris, Crowther, & Houck (2004). Their models indicate that  $\text{Ne}^{2+}$  should be dominant for EZ CMa, and find  $\gamma(\text{Ne}^{2+})$  that is consistent with solar values. The general expectations of massive star evolution (Meynet & Maeder 2003) have been shown consistent with these observations, with neon essentially solar in WN stars and

enriched in WC stars. However, the sample is still rather small with only about 10 stars studied using the method. Our survey nearly doubles the sample.

### 3.1. Line Fitting Procedure

Figure 2 shows spectra for each of our stars centered on the line of [Ne III] 15.56 microns. The specific fluxes are in Janskys. The solid squares are for the observed data, where blends are obvious in many cases. Forbidden lines form at large radii in the constant expansion flow and are optically thin. One thus expects flat-topped rectangular shaped emission lines on top of the continuum. The limited resolution of the IRS leads to more rounded shapes for the lines. In Figure 2, the blend fit is shown as open circles, and the match to [Ne III] alone as the long dashed line. For the forbidden lines, the half-widths of the profiles should represent the asymptotic wind terminal speed. Permitted lines on the other hand form in the vicinity of the IR pseudo-continuum (owing to the strong free-free opacity – Wright & Barlow 1975), and these lines should be narrower since they sample the outer part of the wind acceleration that is below terminal speed. We find that the permitted lines that are blends with [Ne III] can be fit using gaussians with  $\sigma = \epsilon \times v_\infty$ , where  $\epsilon = 0.6$  has been adopted. However, gaussians are too narrow for the forbidden lines because the underlying profile shape is not centrally rounded like recombination lines, but intrinsically rectangular as noted above. We had to adopt a function of similar form to a gaussian to match better the [Ne III] lines, using

$$g(\Delta v) = A_\nu \exp(-\Delta v^4/\sigma_v^4), \quad (1)$$

with  $A_\nu$  an amplitude in Janskys,  $\Delta v$  the observed Doppler shift in km/s, and  $\sigma_v$  a line width. This function provides a symmetric profile shape that has “broader shoulders” as compared to a gaussian profile, required to match the broader forbidden lines just as expected from an underlying rectangular profile shape. For example, the function  $g(\Delta v)$  well approximates the shape that results from convolving a rectangular profile of half-widths appropriate for the WR winds with a gaussian point-spread function of a width appropriate for the resolution of the IRS/SH instrument.

The HWHM for  $g(\Delta v)$  is related to the wind terminal speed via  $\sigma_v = (\ln 2)^{1/4} \times v_\infty \approx 0.91 v_\infty$ . The total emission in the line  $F_l$  comes from integrating  $g(\Delta v)$ , and is analytic as given by

$$F_l = \frac{(\ln 2)^{1/4} v_\infty}{2 \lambda_0} A_\nu \Gamma(1/4), \quad (2)$$

where  $\lambda_0$  is the central (vacuum) wavelength of the line, and  $\Gamma(x)$  is the Gamma function. Our profile fitting allowed up to two nearby line blends along with the forbidden line. A simple algorithm was developed to step through amplitudes, and the best combination of parameters was selected through a reduced chi-square approach.

As a rule, blends were blueward of line center, and at most only a weak feature was ever present redward of [Ne III]. Consequently, the red wing of the forbidden line was used as a gauge for selecting  $\sigma_v$ . Published values of  $v_\infty$  were adopted as initial values used for  $\sigma_v$ , and usually only small changes by 10% or less were needed to match the red wing.

### 3.2. Determination of Ion Fraction Abundances of Ne<sup>2+</sup>

After obtaining fits to [Ne III] 15.56, the ion fraction abundance can be derived, with  $\gamma_{i,E} = Q_i \mathcal{A}_E$ , for  $Q_i$  the ion fraction in stage  $i$  for an element  $E$  with abundance by number  $\mathcal{A}_E$  relative to *all nuclei* (e.g.,  $\mathcal{A}_H \approx 0.92$  for hydrogen in the Sun – Cox 2000). One has the relation  $F_l = \gamma_{i,E} \times F_0$ , where  $F_0$  is a scale constant that depends on atomic parameters for the line transition and parameters for the stellar wind. Following the notation of Ignace & Brimeyer (2006), and correcting for the dependence on clumping as derived by Dessart *et al.* (2000), the scale constant  $F_0$  for the [Ne III] 15.56 transition is given by

$$F_0 = \frac{L_0}{4\pi d^2} = 2.27 \times 10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2} \times \frac{\gamma_e D_c^{1/2}}{d_{\text{kpc}}^2} \left( \frac{\dot{M}_{-5}}{\mu_e v_3} \right)^{3/2}, \quad (3)$$

where  $d_{\text{kpc}}$  is the source distance in kpc, and  $\dot{M}_{-5}$  is corrected for clumping and normalized to  $10^{-5} M_\odot/\text{yr}$ ,  $v_3 = v_\infty/(1000 \text{ km/s})$ ,  $\mu_e$  is the mean molecular weight per free electron,  $\gamma_e = n_i/n_e$  the number of ions per free electron, and  $D_c$  is the wind clumping factor.

One challenge to obtaining ion fraction abundances is the sensitivity of the forbidden line emission to wind clumping. Clumping has long been known to exist in WR winds and can significantly influence observables (e.g., Hillier 1991; Moffat & Robert 1994; Fullerton, Massa, & Prinja 2006;

Puls *et al.* 2006). To describe clumping, we adopt the clumping factor  $D_c$  as the inverse of the volume filling factor  $f_{cl}$ , hence  $D_c = f_{cl}^{-1} = \langle \rho^2 \rangle / \langle \rho \rangle^2$ . Dessart *et al.* (2000) has shown how to correct  $\gamma_{i,E}$  for the influence of clumping. The ion fraction abundance scales as  $\gamma_{i,E} = F_i/F_0 \propto D_c^{-1/2} \dot{M}^{3/2}$ . However, clumping factors are generally derived for the inner wind flow (e.g., Hamann & Koesterke 1998). Although there are observational and theoretical studies of how wind clumping evolves in O star winds (e.g., Runacres & Owocki 2005; Puls *et al.* 2006) and WR winds (e.g., Nugis, Crowther, & Willis 1998; Hillier & Miller 1999), we do not currently know the nature of clumping in the very low density wind of  $10^5 - 10^6 \text{ cm}^{-3}$  associated with the critical densities of common forbidden lines where the line emission predominantly forms. Consequently in future studies, new determinations of wind parameters such as clumping factors will impact inferred values of  $\gamma$  presented here. In computing the value of  $F_0$ , we adopted a collision strength of  $\Omega_{12} = 1.65$  (Pradhan & Peng 1995) at an electron temperature of  $T_e = 10,000 \text{ K}$  (Schmutz & Hamann 1986). In the net  $F_0$  scales weakly with collision strength and temperature as  $F_0 \propto \Omega_{1,2}^{1/2} T_e^{-1/4}$ .

Before presenting derived values of  $\gamma$  for  $\text{Ne}^{2+}$ , it is necessary to discuss how these can be compared against solar abundances and model predictions. In the Sun, the abundance of neon by number is  $\mathcal{A}_\odot(\text{Ne}) = 1.12 \times 10^{-4}$  (Cox 2000). During massive star evolution from O stars through the WN phase, neon is not expected to change its abundance by mass fraction; however, the relative proportion of neon nuclei by number does change owing to the fact that hydrogen is converted to helium. In the limiting case of zero hydrogen in WN stars, one obtains a “renormalized” un-enriched neon abundance by number:

$$\begin{aligned} \mathcal{A}_{WN}(\text{Ne}) &= \frac{\mathcal{A}_\odot(\text{Ne})}{0.25 \mathcal{A}_\odot(\text{H}) + \mathcal{A}_\odot(\text{He})} \\ &= \frac{\mathcal{A}_\odot(\text{Ne})}{(0.25)(0.91) + 0.089} \\ &= 3.54 \times 10^{-4} \\ &\approx 3\mathcal{A}_\odot(\text{Ne}). \end{aligned} \quad (4)$$

Renormalizing the number abundance of neon in relation to WC stars is more complicated. The ratio of C/He is changing throughout this phase, and O/He although minor, it is not entirely trivial. For reference, we ignore O and assume an

equal mass fraction of He and C. Keeping the solar mass fraction of neon unchanged, the renormalized neon abundance by number becomes  $\mathcal{A}_{WC}(\text{Ne}) = 4.48 \times 10^{-4} \approx 4\mathcal{A}_\odot(\text{Ne})$ . Under these assumptions, the value for WC winds is not much different from WN winds because the ratio of C/He by number is still rather low, even though the mass ratio is unity. As an upper limit, converting all of the helium to carbon would give  $\mathcal{A}(\text{Ne}) = 10.6 \times 10^{-4} \approx 9\mathcal{A}_\odot(\text{Ne})$ . However, in our discussion we shall adopt the value for equal mass fractions of He and C as a reference value for determining Ne enrichments.

### 3.3. Notes on Individual Targets

The previous section describes our technique for deriving total line fluxes from [Ne III]. The conversion of these fluxes to ion fraction abundances are described in Barlow *et al.* (1988) for a smooth spherical wind, and by Dessart *et al.* (2000) for one with constant clumping factor. Deriving  $\gamma_{i,E}$  values requires that knowledge about the wind terminal speed, mass-loss rate, clumping factor, and ionization/temperature state. It also requires the distance to the star be known. Stellar and wind parameters for WN stars were taken from Hamann, Gräfener, & Liermann (2006; hereafter HGL06). Those authors employ the Potsdam Wolf-Rayet (PoWR – Hamann & Gräfener 2004) wind models in spherical symmetry to derive wind parameters assuming a constant clumping factor of  $D_c = 4$  for every star. For WC stars, parameters were taken from a variety of studies, as detailed in the description of individual objects to follow.

Distances were taken from these same papers, but in some cases we used photometric distances from the catalogue of Wolf-Rayet stars by van der Hucht (2001; hereafter vdH01). It was found that distances from different sources could vary by a factor of two or more. Since  $\gamma_{i,E}$  scales formally with the square of the distance, this is a significant concern. However, if  $\dot{M}$  is determined from radio excess measurements, then the mass-loss scales with distance as  $\dot{M} \propto d^{3/2}$ . In such cases,  $\gamma_{i,E} \propto d^{1/4}$ , and it has a rather weak dependence on distance. Given measurement errors, uncertainties in continuum placements, line blending effects, and uncertainties in source distances, ion fraction abundances may have a factor of two uncertainty for our weaker sources. But even this is adequate to determine departures from solar metallicity since neon enrichments by factors of

10 or more are expected. The absolute flux calibration of the IRS/SH is good to only about 20% (Decin *et al.* 2004), which may be considered a lower limit to the uncertainty of our neon abundances since they are determined from line fluxes.

Pertinent stellar parameters are listed in Table 1, and derived values of  $\gamma$  for  $\text{Ne}^{2+}$  are given in Table 2. The following sections present brief notes for selected sources. We assume that  $\text{He}^{1+}$  is dominant in the outer winds of WN stars, and that  $\text{He}^{2+}$  is dominant for the WC stars. We also take  $\text{H}/\text{He} = 0$  for each star.

### 3.3.1. WR 94 (WN5)

The ion fraction abundance of  $\text{Ne}^{2+}$  is exceptionally low for this star. The line is actually of similar strength to that observed for WR 1, and in fact the wind parameters are quite similar. The main differences are that WR 94 has about half the terminal wind speed and half the distance of WR 1. This combination leads to an ion fraction abundance around 20% solar. WR 94 shows emission at  $[\text{Ne II}]$  12.81, but its contribution to the neon abundance is even less than  $\text{Ne}^{2+}$ . We cannot explain these low values unless the wind parameters or source distance are in error.

### 3.3.2. WR 52 (WC4)

WR 52 is the earliest of our WC types at WC4, and we have not been able to identify any tailored studies of its wind properties. It does not appear in the study of Koesterke & Hamann (1995; hereafter KH95), which in fact has no analysis for WC stars earlier than WC5. We adopt a photometric distance of 1.5 kpc from vdH01 and a wind speed of  $v_\infty = 2765$  km/s from Prinja, Barlow, & Howarth (1990). The terminal speed is for the average of all the wind lines *except* C IV, for which Prinja *et al.* quote a much faster value of 3225 km/s, a value that we find much too large to match the width of the  $[\text{Ne III}]$  line.

Although KH95 have no WC4 stars from their study, Nugis & Lamers (2000) have two stars in this class. We adopt star and wind parameters based on those two stars (WR 30a and WR 144) in their Table 6. We adopt a clumping factor of  $D_c = 7$  taken from WR 144 (Nugis *et al.* 1998). The resulting neon abundance is suspiciously low, almost solar, possibly indicating that in this early WC star,  $\text{Ne}^{3+}$  may be the dominant ion stage instead of  $\text{Ne}^{2+}$ .

### 3.3.3. WR 111 (WC5)

We use star and wind parameters for WR 111 from the tailored analysis of Gräfener & Hamann (2005). These authors use a mass fraction of Si of  $0.8 \times 10^{-3}$ . With their values for He and C, we derive a Si abundance of  $2 \times 10^{-4}$  by number. The neon-to-silicon abundance for the Sun is 3.47 (Cox 2000). With  $\gamma = 29 \times 10^{-4}$  for  $\text{Ne}^{2+}$ , this implies  $\text{Ne}^{2+}/\text{Si} \geq 15$ . No processing of silicon is expected until very late stages of massive star evolution, so the implication is that neon is enriched by a factor of  $\approx 4$ , or more if some neon exists in  $\text{Ne}^{3+}$ , and consistent with the value of 6.5 in Table 2. It is worth noting that using parameters derived from an independent study by Hillier & Miller (1999) yields a Ne abundance that is about 50% greater in value, due mostly to a smaller value of the volume filling factor.

### 3.3.4. WR 5 (WC6)

A photometric distance of 1.9 kpc is adopted from vdH01. Wind and stellar parameters are taken from KH95, except that we lower the mass-loss rate by a factor 3 assuming a nominal clumping factor of  $D_c = 9$ .

### 3.3.5. WR 90 (WC7)

The star with our latest WC type is WR 90, at WC7. Stellar parameters from Dessart *et al.* (2000) are adopted. Those authors obtained ISO data of a similar spectral range as our *Spitzer* data. They measured  $F_l = 6.5 \times 10^{-12}$  erg/s/cm<sup>2</sup> from  $[\text{Ne III}]$  15.56. Our derived value is a little more than twice the value of that paper. However, the data of Dessart *et al.* are quite noisy, and without knowing how their data were processed or where their continuum level was placed, it is difficult to determine the cause of this difference.

## 4. Conclusions

Our survey approximately doubles the sample of neon abundances derived for Galactic WC stars, and substantially increases the number of such instances at spectral subtypes of high ionization (earlier than WC8). Our analysis of  $[\text{Ne III}]$  15.56 microns of four WN stars and four WC stars appear generally consistent with the expectations of massive star evolution theory (Maeder 1983; Meynet & Maeder 2003): (1) The ion fraction abundances of  $\text{Ne}^{2+}$  are consistent with solar proportions of neon in the WN stars as expected, and (2) those for the WC stars show enhanced values of

Ne<sup>2+</sup>. Formally, our derived values are lower limits to the neon abundances in the sense that neon can exist in more than one ion stage. At large radii where the forbidden line forms, He<sup>1+</sup> or He<sup>2+</sup> will be dominant, and a consideration of IPs suggests that Ne<sup>2+</sup> will probably be the dominant ion for many WR winds. Our survey does not include lower ionization WR stars, such as the WN8-10 and WC8-9 stars, where Ne<sup>1+</sup> is more likely to be a significant ion stage of neon (c.f., discussion of Houck & Smith 2005). However, uncertainties in distance, deblending, continuum placement, and clumping factors may allow for a factor of two uncertainty in derived ion fraction abundances of Ne<sup>2+</sup> in some of our weaker sources.

It is worth commenting that our understanding of wind clumping and its distribution throughout hot star winds is still somewhat poor. As a limit, should clumping disappear altogether in the very low density outer wind (e.g., Puls *et al.* 2006 find empirically that clumping decreases with radius in O star winds), all of the values of  $\gamma(\text{Ne}^{2+})$  would double for the WN stars (and still remain largely solar), but triple or more for the WC stars. On the other hand, if the winds become increasingly clumped, our  $\gamma$  values would need to be revised downward. Taking straight averages, the ratio of Ne<sup>2+</sup> for the four WC stars as compared to that of the four WN stars is almost a factor of 9.

As one final note, in drawing conclusions about neon abundances for our sources, we have adopted solar abundances from Cox (2000). Morris *et al.* (2004) and Smith & Houck (2005) both reference the Asplund *et al.* (2004) value of solar neon that is 1.8 times smaller than Cox (2000). Such a value would nearly double the neon enrichments inferred for the stars of our sample. It is clear that future progress in the quantitative assessment of massive star evolution theory against observational data will require several things: better distances to WR stars, better knowledge of wind clumping factors, and a resolution to the appropriate neon abundance for use as a reference point of chemical enrichments.

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TABLE 1  
SUMMARY OF STAR PROPERTIES

Target	Type	$d$ (kpc)	$v_\infty$ (km/s)	$\dot{M}$ ( $M_\odot/\text{yr}$ )	$\gamma_e$	$\mu_e$
WR 1	WN4	1.8	2100	$2.0 \times 10^{-5}$	1.0	4
WR 94	WN5	1.1	1300	$2.0 \times 10^{-5}$	1.0	4
WR 75	WN6	4.0	2300	$7.9 \times 10^{-5}$	1.0	4
WR 74	WN7	4.0	1300	$2.5 \times 10^{-5}$	1.0	4
WR 52	WC4	1.5	2765	$1.2 \times 10^{-5}$	0.5	3
WR 111	WC5	1.6	2300	$0.7 \times 10^{-5}$	0.5	2.5
WR 5	WC6	1.9	2100	$1.6 \times 10^{-5}$	0.5	3
WR 90	WC7	1.6	2045	$2.5 \times 10^{-5}$	0.5	3

TABLE 2  
RESULTS OF LINE ANALYSES

Target	Type	$F_c(15.56\mu\text{m})^a$ (Jy)	$A_\nu$ (Jy)	$\sigma_v$ (km/s)	$D_c$	$F_l$ (erg/s/cm <sup>2</sup> )	$\gamma$ (Ne <sup>2+</sup> )	Ne <sup>2+</sup> (Ne <sub>⊙</sub> ) <sup>b</sup>
WR 1	WN4	0.43	0.18	2300	4	$4.4 \times 10^{-13}$	$4.0 \times 10^{-4}$	1.1
WR 94	WN5	0.47	0.13	1200	4	$1.7 \times 10^{-13}$	$0.75 \times 10^{-4}$	0.21
WR 75	WN6	0.36	0.32	2300	4	$7.9 \times 10^{-13}$	$2.4 \times 10^{-4}$	0.67
WR 74	WN7	0.21	0.26	1100	4	$3.1 \times 10^{-13}$	$2.6 \times 10^{-4}$	0.74
WR 52	WC4	0.07	0.16	2600	$\approx 7^c$	$4.3 \times 10^{-13}$	$10. \times 10^{-4}$	2.3
WR 111	WC5	0.66	1.4	2500	50	$38 \times 10^{-13}$	$35 \times 10^{-4}$	7.7
WR 5	WC6	0.23	0.67	2100	9	$15 \times 10^{-13}$	$15 \times 10^{-4}$	3.5
WR 90	WC7	1.24	6.7	2100	10	$150 \times 10^{-13}$	$46 \times 10^{-4}$	10.

<sup>a</sup>Specific flux of the continuum at 15.56  $\mu\text{m}$  based on our fit to the data.

<sup>b</sup>The solar neon abundance is the transformed value for WN ( $3.54 \times 10^{-4}$ ) or WC stars ( $4.48 \times 10^{-4}$ ), respectively, as described in the text. The adopted abundance of neon for the Sun was taken from Cox (2000). All abundances approximately double if normalizing to the value from Asplund *et al.* (2004).

<sup>c</sup>This value is for the WC4 star, WR 144, inferred from Tab. 6 of Nugis *et al.* (1998).



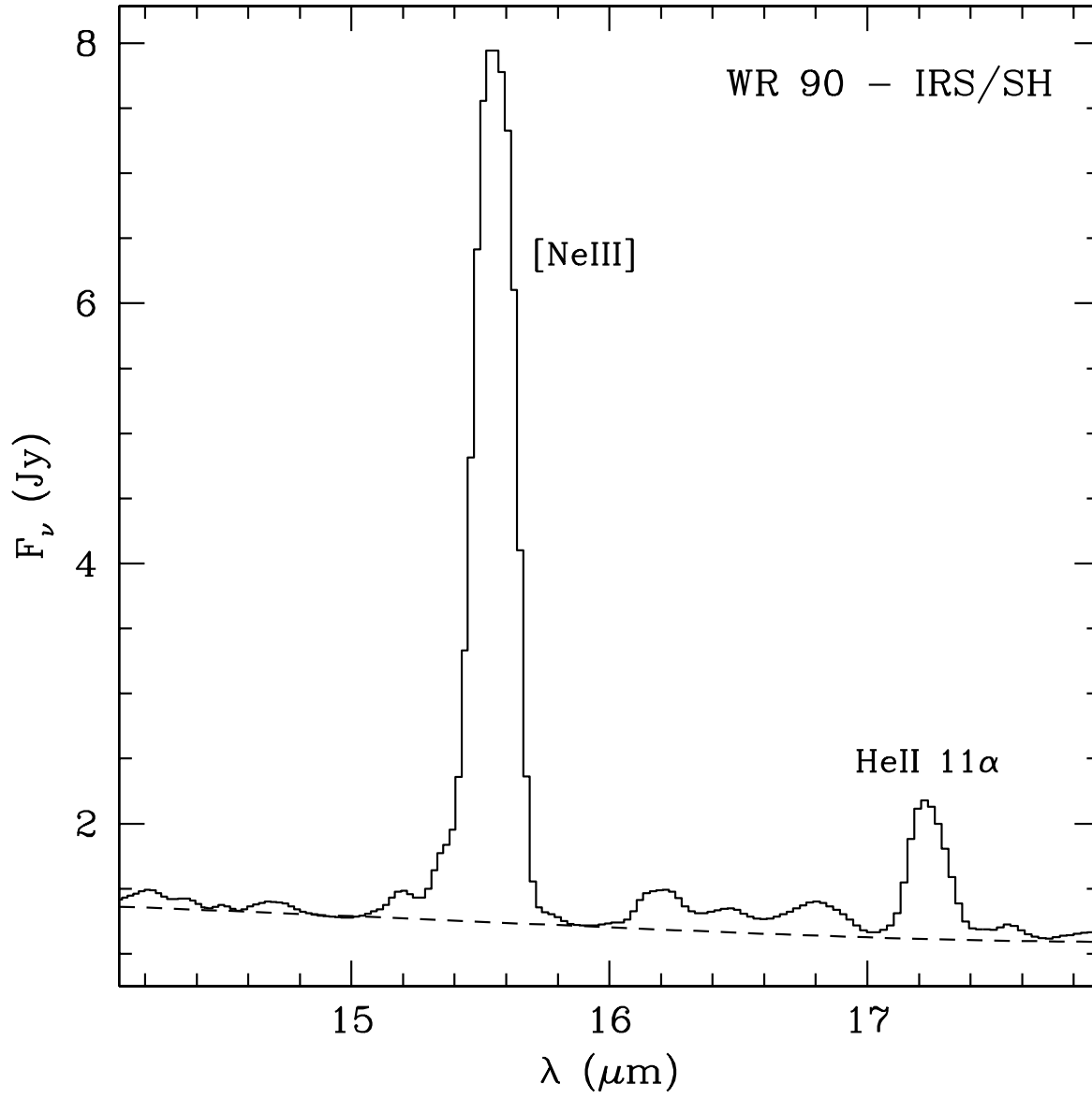


Fig. 1.— *Spitzer* IRS/SH spectra in the neighborhood of [Ne III] 15.56 for WR 90. The line shows weak line blends on the blue side of the profile. The He II 11 $\alpha$  line is seen to the far right of this plot. The solid curve is the data, and the dashed one is for our fit to the continuum that is subtracted from the data in order to obtain the total flux of emission in the line of [Ne III].

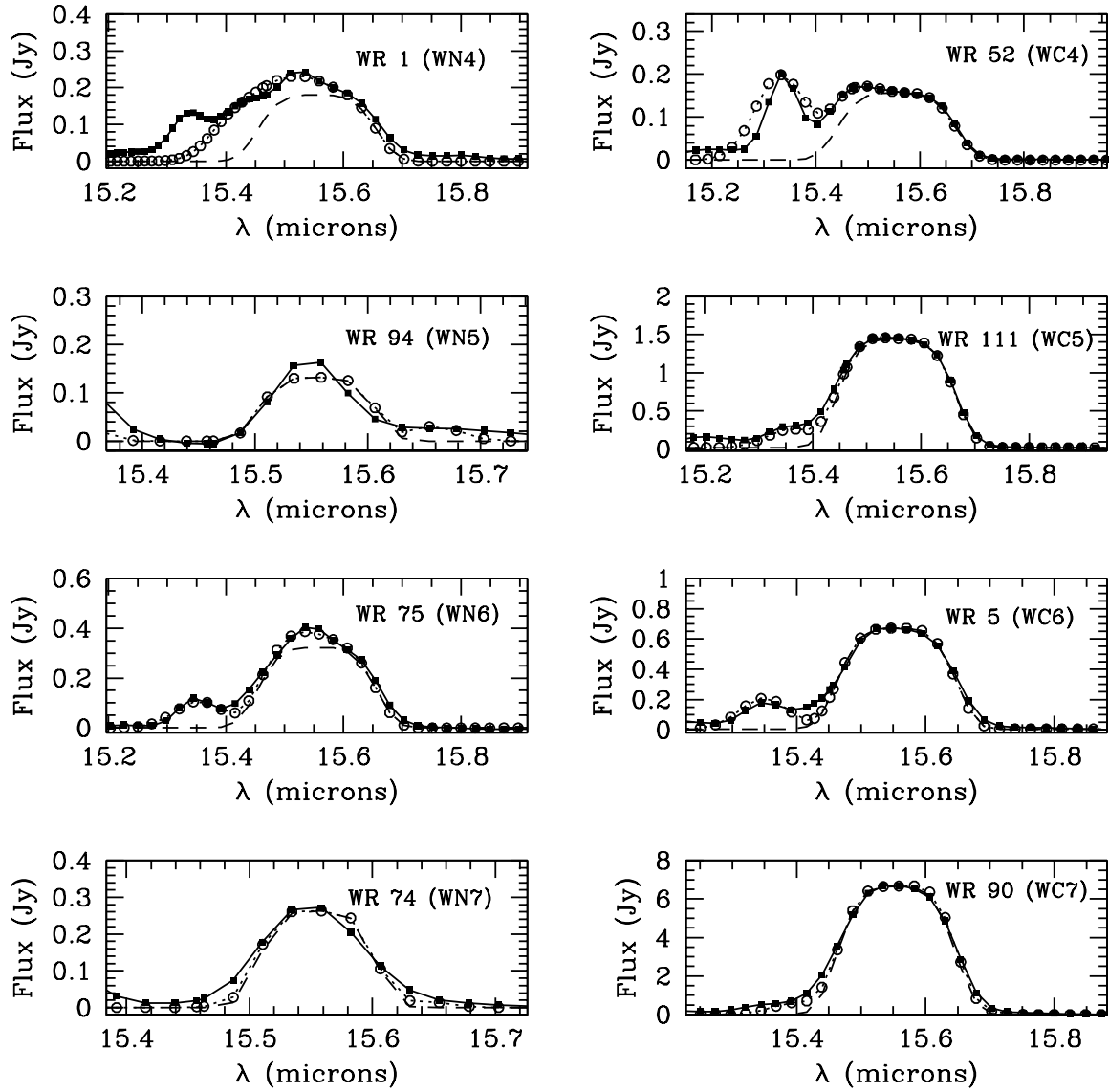


Fig. 2.— *Spitzer* IRS/SH spectra of our eight target sources centered at [Ne III] 15.56. The data are continuum subtracted, and with no dereddening applied. Solid squares are the data; open circles are fits to the lines with blends; and the long-dashed line shows the isolated fit profile for [Ne III]. Details regarding the profile fitting are described in the text.